Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 2 February 2008 (MN LaTeX style file v1.4)

SAX J1808.4-3658 and the origin of X-ray variability in X-ray binaries and active galactic nuclei

Philip Uttley*

School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ

2 February 2008

ABSTRACT

The aperiodic X-ray variability in neutron star and black hole X-ray binaries (XRBs), and active galactic nuclei (AGN) shows a characteristic linear relationship between rms amplitude and flux, implying a multiplying-together or 'coupling' of variability on different time-scales. Such a coupling may result from avalanches of flares, due to magnetic reconnection in an X-ray emitting corona. Alternatively this coupling may arise directly from the coupling of perturbations in the accretion flow, which propagate to the inner emitting regions and so modulate the X-ray emission. Here, we demonstrate explicitly that the component of aperiodic variability which carries the rms-flux relation in the accreting millisecond pulsar SAX J1808.4-3658 is also coupled to the 401 Hz pulsation in this source. This result implies that the rms-flux relation in SAX J1808.4-3658 is produced in the accretion flow on to the magnetic caps of the neutron star, and not in a corona. By extension we infer that propagating perturbations in the accretion flow, and not coronal flares, are the source of the rms-flux relations and hence the aperiodic variability in other XRBs and AGN.

Key words: X-rays: binaries – X-rays: individual: SAX J1808.4-3658 – X-rays: galaxies – galaxies: active – accretion – instabilities

1 INTRODUCTION

Aperiodic X-ray variability, occuring over a broad range of time-scales in the form of 'flicker noise' or 'band-limited noise' is a ubiquitous characteristic of X-ray binary systems (van der Klis, 1995) and active galaxies (M^{c}Hardy 1988; Uttley, M^{c}Hardy & Papadakis 2002; Markowitz et al. 2003). The origin of this variability is not well understood. Recently, a new fundamental property of the aperiodic variability in XRBs and AGN was discovered: the rms-flux relation (Uttley & M^{c}Hardy, 2001). Specifically, there exists a strong linear correlation between the amplitude of X-ray variability on short time-scales and the X-ray flux as measured on longer time-scales (Uttley & M^{c}Hardy 2001; Edelson et al. 2002; Vaughan, Fabian & Nandra 2003). Since the flux variations on all the time-scales probed in these studies are dominated by the aperiodic variability, this linear 'rms-flux relation' implies that aperiodic variations on longer time-scales modulate the aperiodic variations on shorter time-scales, i.e. the aperiodic variations on different time-scales are coupled together.

Importantly, the observed linear rms-flux relations, which occur over a broad range of time-scales, cannot be explained if the variability is produced by simple shot-noise models where the light curve is produced by the summation of randomly occuring shots or flares which are independent of one another (see Uttley & M^{c}Hardy 2001 for a detailed discussion). Instead the shots must be coupled together. For example, the shots may correspond to fractal structures, e.g. flares that break into smaller structures, which in turn break up and so on, producing a coupling between larger slower variations and smaller faster ones. Alternatively, the required coupling may be produced if flares trigger avalanches of smaller flares (e.g. similar to the model of Stern & Svensson 1996). A natural interpretation of such models is that they correspond to flares due to magnetic reconnection in the corona (Poutanen & Fabian, 1999), so we refer to this class of explanations for the variability as the 'coronal-flare' or CF model.

Alternatively, a linear rms-flux relation can be naturally produced by the model of Lyubarskii (1997), where the variability is caused by variations in accretion rate occuring at different radii (with slower variations occuring at larger radii), which propagate inwards and modulate the X-ray emitting region and hence the X-ray light curve. In this model, the amplitudes of accretion rate variations produced at a given radius scale with the local accretion rate at that radius (which is driven by the slower variations that

* E-mail: pu@astro.soton.ac.uk

originated at larger radii) and hence variations on different time-scales are coupled together. In fact, any model of propagating perturbations in the accretion flow (e.g. density waves, Misra 2000) could produce a linear rms-flux relation provided the perturbations can couple linearly together. We will call this class of explanations for the variability the 'propagating perturbation' or PP model.

In this Letter, we point out that the CF and PP models can be distinguished in the case of accreting neutron star XRBs, which show a linear rms-flux relation in their aperiodic X-ray variability, provided that it can be shown that the aperiodic X-ray variability containing the rms-flux relation originates on or close to the neutron star surface, and hence cannot be associated with coronal flares. We demonstrate explicitly that the accreting millisecond X-ray pulsar SAX J1808.4-3658 fulfils these criteria, so that the CF model can be ruled out in this case and the PP model is the most likely explanation for the aperiodic variability and the rms-flux relation in this system. We then infer that the PP model is also the correct explanation for the aperiodic variability which shows a linear rms-flux relation in other XRBs, and AGN, before discussing the further implications of this result.

2 THE ORIGIN OF THE RMS-FLUX RELATION IN SAX J1808.4-3658

In Uttley & M^{c}Hardy (2001) we demonstrated that the linear rms-flux relation is observed in the aperiodic X-ray variability of the accreting millisecond X-ray pulsar SAX J1808.4-3658. Due to its highly coherent 401 Hz X-ray pulsations (Wijnands & van der Klis, 1998a) SAX J1808.4-3658 is a confirmed NS system, and offers the possibility of directly testing the CF and PP models for aperiodic X-ray variability, if it can be shown that the X-ray variability originates on or close to the neutron star surface. This is because although the CF model requires that the X-ray variability originates in a flaring corona, the PP model does not require a specific physical origin for the X-ray emission, provided that the perturbations in the accretion flow can propagate in to the X-ray emitting region (whether this is an accretion powered corona or the surface of a neutron star) and so modulate the X-ray emission.

2.1 Coupling of the 401 Hz pulse and aperiodic flux variations

Evidence that much of the X-ray emission in neutron star XRBs originates at the neutron star surface (or some boundary layer close to the surface) comes from comparisons of X-ray spectra of neutron star and black hole candidate systems (Done & Gierlinski, 2003). Fourier-frequency resolved analysis of neutron star XRB spectral variability confirms this result and further suggests that some component of the variability originates at the neutron star surface or boundary layer, provided certain plausible assumptions are made about the spectral shape of emission from that surface (Gilfanov, Revnivtsev & Molkov, 2003). However, we require more model-independent evidence that the aperiodic variability in SAX J1808.4-3658 originates at or close to this surface. Interestingly, such evidence is provided by a coupling

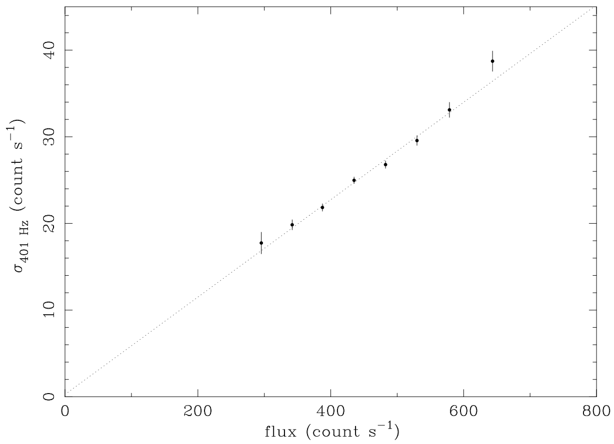

Figure 1. The rms-flux relation of the 401 Hz pulsation in SAX J1808.4-3658. Standard (1σ) errors are determined from the spread of the individual 401 Hz power measurements binned together in the averaged PSDs. The dotted line shows the linear best-fitting model described in the text.

between the aperiodic variability and the 401 Hz pulsation in this system, which has been inferred from a broadening of the pulse peak measured in the power spectrum of this source (Menna et al., 2003). This result implies that a significant component of the aperiodic X-ray variations originates on the neutron star surface, at the accretion-fed magnetic caps, and is modulated at the spin frequency to produce the observed coupling.

The method used by Menna et al. (2003) to demonstrate coupling between the aperiodic and periodic variability in SAX J1808.4-3658 tests the assumption that the observed power spectrum results from a simple convolution of the Fourier transforms of aperiodic and periodic variations. In the time domain, this assumption corresponds to the case where the light curve of aperiodic variations is multiplied by a sinusoidal pulse light curve with a mean of unity and an rms equal to the fractional rms of the pulse. Then it is easy to see that a prediction of the coupling of the pulse and aperiodic variability reported by Menna et al. (2003) is that the *absolute* rms of the pulse should scale linearly with the aperiodic flux variations, i.e. the pulse will itself show a linear rms-flux relation.

To test this prediction we used data from a *Rossi X-ray Timing Explorer* (RXTE) observation of SAX J1808.4-3658 used by Uttley & M^{c}Hardy (2001) and Menna et al. (2003)[†]. A 2-20 keV light curve (with 2^{-11} s resolution), of 23 ks exposure was extracted from the data and split into segments of 1 s length. The power spectrum and flux (count rate) was measured for each individual segment, and the power spectra of many segments were averaged together according to their flux (here, power spectra are measured in rms^2 units, i.e. not normalised by the square of the mean flux). We estimated the noise level directly from the data by fitting a power-law to the surrounding 200 Hz window of data, centred on but excluding the peak at 401 Hz, and took the square-root of the noise-subtracted power at 401 Hz (directly equivalent to

† Observation IDs 30411-01-06-000, 30411-01-06-00 observed 1998 April 18

the integrated power or variance, since the frequency resolution is 1 Hz) to obtain the absolute rms of the pulse as a function of flux. The resulting rms-flux relation is shown in Fig. 1. A linear fit to the data provides a good fit ($\chi^2 = 8$ for 6 degrees of freedom), and yields an offset on the flux axis consistent with zero (flux offset $C = -5 \pm 38$ count s^{-1}, errors are 90% confidence).

2.2 Coupling of the pulse to the aperiodic variability amplitude

The linear rms-flux relation shown by the pulse confirms that aperiodic and periodic variations are coupled, and therefore at least some component of the aperiodic X-ray variability must originate at or close to the magnetic caps of the neutron star. However, this does not necessarily imply that the component of aperiodic X-ray variability showing a linear rms-flux relation also originates at the same location. For example, if a component with a linear rms-flux relation, which is not coupled to the pulse, contributes a similar flux to a component with constant rms which is coupled to the pulse, both the pulse and aperiodic rms-flux relations can be preserved. This is because the highest and lowest total observed fluxes correspond to the times when the fluxes of *both* aperiodic components are high and low respectively. Hence, when the total flux is high both the pulse rms and the aperiodic rms will be high, and the rms of the pulse and aperiodic variability will both be low when the total flux is low.

However, in the case where the aperiodic rms-flux relation is produced in a separate component to the pulsed component of aperiodic variability, we expect that the amplitude of the aperiodic variability and the rms of the pulse will not be correlated. To demonstrate this fact, we use simulated light curves. As shown in Uttley, M$^{\rm c}$Hardy & Vaughan (2003) and Uttley, M$^{\rm c}$Hardy & Vaughan (in prep.), aperiodic light curves with a linear rms-flux relation on all time-scales may be simply generated by replacing each data point in a linear light curve (e.g. generated using the algorithm of Timmer & König 1995) with its exponential. We examined two cases:

(i) The aperiodic variability is produced by a single component with a linear rms-flux relation on all time-scales, which is modulated by a sine wave at the pulse frequency (i.e. in its simplest form this model corresponds to the case where the rms-flux relation is produced at the magnetic caps of the neutron star).

(ii) The aperiodic variability is produced in equal parts by two components: a linear component with rms independent of flux (which is modulated by a sine wave at the pulse frequency), and an unpulsed component with a linear rms-flux relation on all time-scales (i.e. the rms-flux relation is produced in a different location to the magnetic caps, e.g. in a corona).

In both cases, the simulated aperiodic variability assumed a broken power-law power spectrum with power-law slope 0 below 0.3 Hz and -1 at higher frequencies (up to the Nyquist frequency), to approximate the observed power spectrum (Wijnands & van der Klis, 1998b). The simulated amplitudes of variability (combined amplitude in case (ii)) were

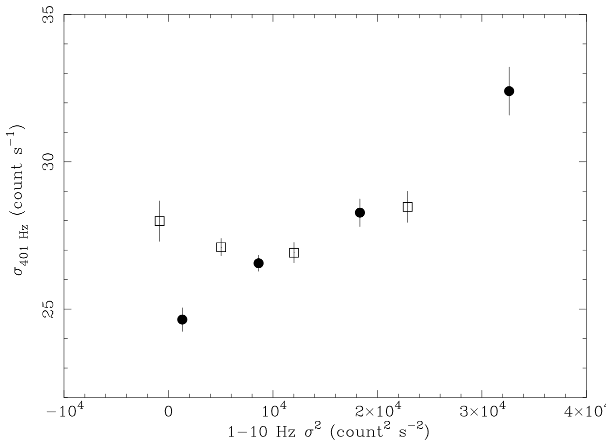

Figure 2. Pulsation rms versus aperiodic 1-10 Hz variance for simulated light curves of SAX J1808.4-3658. Filled circles denote case (i), where a single component of aperiodic variability containing the linear rms-flux relation is modulated by the pulse. Open squares denote case (ii), where there are two aperiodic components and the pulse is only coupled to the component which has rms independent of flux. Errors are determined using the same method as for Fig. 1.

chosen to match that of the source, and Poisson noise corresponding to the observed source plus background count rates was also included.

To examine the correlation between the amplitude of aperiodic variability and the pulse amplitude, we averaged together the 1 s measurements of the power spectrum (discussed in Section 2.1) according to their noise-subtracted variance (i.e. integrated power) measured in the 1-10 Hz band, to obtain the pulse rms as a function of the aperiodic 1-10 Hz variance. We bin the pulse rms as a function of 1-10 Hz variance rather than rms, because in individual 1 s segments the true noise level may exceed the estimated value, which can lead to negative noise-subtracted variance, so that rms cannot be determined (e.g. see discussion in Uttley & M$^{\rm c}$Hardy 2001, Gleissner et al. 2003).

Fig. 2 shows the pulse rms versus aperiodic variance for the case (i) and case (ii) simulations described above. Case (i), where the pulsed aperiodic variability contains a linear rms-flux relation, shows a clear correlation between pulse rms and aperiodic variance, with a linear plus constant model χ^2 fit yielding a positive gradient $(2.3\pm0.4)\times10^{-4}$ for $\chi^2 = 1.3$ for 2 degrees of freedom (errors are 90% confidence limits). Note that the increase in pulse rms with aperiodic variance is relatively small, because the aperiodic variance contains a large amount of intrinsic scatter, unrelated to the rms-flux relation, due to the stochastic nature of the variability and the effects of noise. Nonetheless, a significant correlation between pulse rms and aperiodic variance is easily seen. Case (ii), on the other hand, shows no such correlation (gradient $(0.4 \pm 0.5) \times 10^{-4}$ for $\chi^2 = 5.9$, for 2 degrees of freedom), due to the fact that the pulsed aperiodic component does not contain the linear rms-flux relation. Note that the spread in 1-10 Hz variance is larger in case (i) than in case (ii) because of the stronger rms-flux relation (which applies to the entire light curve) in case (i), but the average variance is the same in both cases.

In Fig. 3 we plot the observed pulse rms versus aperi-

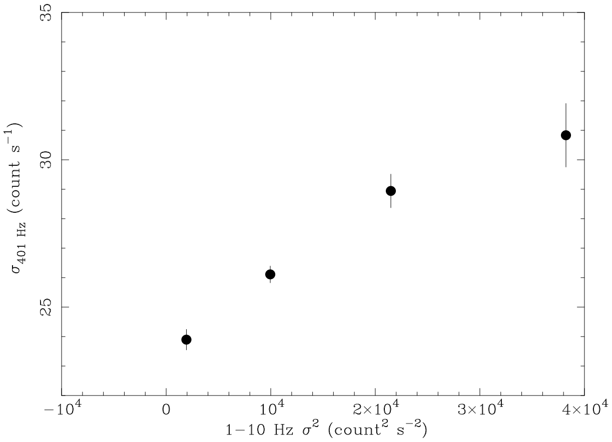

Figure 3. Observed pulsation rms versus aperiodic 1-10 Hz variance for 2-20 keV light curve of SAX J1808.4-3658. Errors are determined using the same method as for Fig. 1.

odic variance. The pulse rms and the aperiodic variance are clearly correlated (gradient $(2.2\pm0.4)\times10^{-4}$ for $\chi^2 = 3.2$, for 2 degrees of freedom). Furthermore, the observed gradient of the correlation is consistent with that predicted by the case (i) simulated data. Therefore, we conclude that the aperiodic variability containing the linear rms-flux relation is coupled to the pulse, and furthermore, no additional component of aperiodic variability is required by the data. Thus we infer that the X-ray variability carrying the rms-flux relation originates at the magnetic caps of the neutron star and therefore the PP model is correct in SAX J1808.4-3658 and the CF model is ruled out. For completeness, we note here the possibility that case (i) corresponds to a more complicated PP model, where most of the aperiodic variability is produced before the pulsed variability by perturbations propagating through a separate unpulsed emitting region (e.g. a static corona above the disk), before reaching the site of the pulsed emission. However, given the available spectral-variability evidence for other neutron stars (Gilfanov, Revnivtsev & Molkov, 2003), it is simplest to assume that all the variable emission originates at or close to the neutron star surface.

3 DISCUSSION

We have demonstrated that the aperiodic X-ray variations which contain the linear rms-flux relation in SAX J1808.4-3658 are coupled to the 401 Hz pulsation, and hence originate on or close to the magnetic caps of the neutron star. The only existing model which can explain this result is the PP model: specifically, the rms-flux relation is produced by the coupling of perturbations in the accretion flow as they propagate inwards. When the accretion flow is channeled on to the magnetic caps of the neutron star, the energy of accretion is released and the pattern of fluctuations in the accretion flow (including the rms-flux relation) is imprinted on the resulting X-ray emission.

Although we have only shown that the PP model is the most likely explanation of the rms-flux relation in SAX J1808.4-3658, it seems highly likely also that the PP model explains the aperiodic variability and rms-flux relation in other accreting neutron star and black hole systems (including AGN). For example, the power spectra of broad-band noise in both black hole and neutron star XRBs (including SAX J1808.4-3658) can be described by a simple model involving the superposition of broad Lorentzian features (Belloni, Psaltis & van der Klis 2002; Pottschmidt et al. 2003; van Straaten, van der Klis & Wijnands 2003), and both neutron star and black hole systems show similar correlations between the different characteristic frequencies of these features (e.g. Wijnands & van der Klis 1999; Belloni, Psaltis & van der Klis 2002; Pottschmidt et al. 2003). The strong similarities between black hole XRB variability and that of AGN, with characteristic time-scales apparently scaling with the black hole mass (e.g. Uttley, M^{c}Hardy & Papadakis 2002; Markowitz et al. 2003; M^{c}Hardy et al. 2003) also strongly support the idea that AGN and XRBs share the same aperiodic variability mechanism. Since the light curves of all these types of system show a linear rms-flux relation (e.g. Uttley & M^{c}Hardy 2001; Vaughan, Fabian & Nandra 2003; Gleissner et al. 2003), the application of Ockham's Razor would suggest that the rms-flux relation is produced by the same mechanism in all cases and hence the aperiodic X-ray variability in neutron star and black hole XRBs and AGN is produced by a PP mechanism, and not by coronal flares.

It should be restated here that the PP interpretation of the variability does not carry any implications for the existence of an X-ray emitting corona. This is because the aperiodic variability (and the rms-flux relation imprinted in it) is produced in the accretion flow and is independent of where the X-rays are emitted, provided that variations in the accretion flow can modulate the X-ray emission. Thus a corona which is heated by many small reconnection events (too small to have a very strong effect on the variability) remains a viable source of the X-ray emission (in black hole systems, at least). In fact, by invoking an extended X-ray emitting region (such as a corona) which possesses a temperature gradient, so that higher energy X-rays are preferentially emitted closer to the black hole, PP-type models naturally produce the time-dependent delays between energy bands and the energy-dependent shape of the power spectrum, which are observed in black hole X-ray binaries (e.g. Misra 2000; Kotov, Churazov & Gilfanov 2001; Zycki 2003) and AGN (e.g. Vaughan, Fabian & Nandra 2003; M^{c}Hardy et al. 2003).

We have recently shown (Uttley, M^{c}Hardy & Vaughan 2003, and Uttley et al., in prep.) that the existence of an rms-flux relation on all time-scales leads naturally to the appearance of non-linear behaviour which is observed over a range of time-scales in both XRBs (Maccarone & Coppi 2002; Gierlinski & Zdziarski 2003) and AGN (Uttley et al. 1999; Gliozzi et al. 2002), Although the PP model is not a necessary explanation for such behaviour (which is a phenomenological outcome of the rms-flux relation), it provides a natural physical framework for understanding it, in that the PP model appears to be the correct physical explanation for the rms-flux relation.

The PP model allows a simple understanding of other aspects of the variability. For example, the characteristic time-scales observed in the variability of XRBs and AGN can be understood in terms of time-scales in the accretion flow (e.g. the broad Lorentzian features can be formed if perturbations are produced over certain narrow ranges of

radii), thus potentially unifying models for the aperiodic variability with models for quasi-periodic oscillations that are sometimes observed in XRBs (though not yet conclusively in AGN). What physical time-scales these characteristic features correspond to is not yet clear. The PP model requires that perturbations are produced at different radii in the accretion flow, that these perturbations can propagate inwards without being suppressed (e.g. damped by viscous dissipation), and that the perturbations produced at different radii can couple together. A possible configuration which could fulfil these criteria is a geometrically thick accretion flow (such as a thick disk, or an advection dominated accretion flow), where accretion time-scales are relatively short so that variations, e.g. on the thermal time-scale, can propagate to the inner regions of the accretion flow without being significantly damped (Manmoto et al. 1996; Churazov, Gilfanov & Revnivtsev 2001). Alternatively, the fact that a linear rms-flux relation is observed in Cyg X-1 in both the soft and hard states has been used by Gleissner et al. (2003) to suggest that the variations originate in a coronal accretion flow (rather than a disk), which should also show a short accretion time-scale and hence might satisfy the PP model requirements. The physical origin of the perturbations is unclear, although a variety of well-known accretion instabilities could contribute (Frank, King & Raine, 1992). Furthermore, King et al. (2003) have recently shown that MHD turbulence can cause accretion perturbations on sufficiently long time-scales for a linear rms-flux relation to be produced by the inward propagation and coupling of the perturbations.

Finally, we note that a PP model origin for aperiodic variability in XRBs and AGN implies that the variability can be used to probe the location and structure of the X-ray emitting regions close to the neutron star surface or black hole event horizon. For example, an extended emitting region acts as a low pass filter, suppressing variations which originate within the emitting region relative to slower variations which originate outside, for the simple reason that an inward-propagating perturbation can only modulate emission within the radius at which it is formed. This simple picture can help to explain why neutron star XRBs show stronger high-frequency noise (at frequencies > 10 Hz) than black hole systems (Sunyaev & Revnivtsev, 2000), i.e. because their X-ray emission originates predominantly on the neutron star surface, within the radius where the highest frequency accretion flow perturbations are produced. Similarly, in black hole systems the suppression of variability within a coronal emitting region with a temperature gradient will lead to energy dependent power-spectral shapes, which can be used to constrain the radial emission structure of the corona (Kotov, Churazov & Gilfanov 2001; Zycki 2003).

4 CONCLUSIONS

We have demonstrated that the aperiodic variability which carries the linear rms-flux relation in the accreting millisecond pulsar SAX J1808.4-3658, is coupled to the 401 Hz pulsation in this source, and hence the component of X-ray emission which contains the rms-flux relation is produced at the magnetic caps of the neutron star. We conclude that the aperiodic variability is produced by inward-propagating perturbations in the accretion flow on to the neutron star, with the rms-flux relation produced by a coupling of perturbations produced on different time-scales. By extension, this result suggests that the same mechanism produces the rms-flux relations observed in black hole XRBs and AGN, so that the aperiodic X-ray variability in all these diverse systems is caused by perturbations in the accretion flow, and not by flares due to magnetic reconnection in the corona.

Acknowledgments

We wish to thank the anonymous referee for helpful comments.

References

Belloni T., Psaltis D., van der Klis M., 2002, ApJ, 572, 392
Churazov E., Gilfanov M., Revnivtsev M., 2001, MNRAS, 321, 759
Done C., Gierlinski M., 2003, MNRAS, 342, 1041
Edelson R., Turner T. J., Pounds K., Vaughan S., Markowitz A., Marshall H., Dobbie P., Warwick R., 2002, ApJ, 568, 610
Frank J., King, A. R., Raine D. J., 1992, Accretion Power in Astrophysics. Cambridge Univ. Press, Cambridge
Gierlinski M., Zdziarski A. A., 2003, MNRAS, 343, L84
Gilfanov M., Revnivtsev M., Molkov S., 2003, A&A, 410, 217
Gleissner T., Wilms J., Pottschmidt K., Uttley P., Nowak M. A., Staubert R., 2003, A&A in press (astro-ph/0311039)
Gliozzi M., Brinkmann W., Räth C., Papadakis I. E., Negoro H., Scheingraber H., 2002, A&A, 391, 875
King A. R., Pringle J. E., West R. G., Livio M., 2003, MNRAS in press (astro-ph/0311035)
Kotov O., Churazov E., Gilfanov M., 2001, MNRAS, 327, 799
Lyubarskii Yu. E., 1997, MNRAS, 292, 679
Maccarone T. J., Coppi P. S., 2002, MNRAS, 336, 817
M^{c}Hardy I. M., 1988, MmSAI, 59, 239
M^{c}Hardy I. M., Papadakis I. E., Uttley P., Page M. J., Mason K. O., 2003, submitted to MNRAS
Manmoto T., Takeuchi M., Mineshige S., Matsumoto R., Negoro H., 1996, ApJ, 464, L135
Markowitz A., et al., 2003, ApJ, 593, 96
Menna M T., Burderi L., Stella L., Robba N., van der Klis M., 2003, ApJ, 589, 503
Misra R., 2000, ApJ, 529, L95
Pottschmidt K., et al., 2003, A&A, 407, 1039
Poutanen J., Fabian A. C., 1999, MNRAS, 306, L31
Stern B. E., Svensson, R., 1996, ApJ, 469, L109
Sunyaev R., Revnivtsev M., 2000, A&A, 358, 617
Timmer J., König M., 1995, A&A, 300, 707
Uttley P., M^{c}Hardy I. M., Papadakis I. E., Guainazzi M., Fruscione A., 1999, MNRAS, 307, L6
Uttley P., M^{c}Hardy I. M., 2001, MNRAS, 323, L26
Uttley P., M^{c}Hardy I. M., Papadakis I. E., 2002, MNRAS, 332, 231
Uttley P., M^{c}Hardy I. M., Vaughan S., 2003, in Collin S., Combes F., Shlosman I., eds, ASP Conf. Ser., Vol. 290, p. 131

van der Klis M., 1995, in Lewin H. G., Van Paradijs J., van den Heuvel P. J., eds, X-Ray Binaries. Cambridge Univ. Press, Cambridge, p. 252
van Straaten S., van der Klis M., Wijnands R., 2003, astro-ph/0309345
Vaughan S., Fabian A. C., Nandra K., 2003, MNRAS, 339, 1237
Wijnands R., van der Klis M., 1998a, Nat, 394, 344
Wijnands R., van der Klis M., 1998b, ApJ, 507, L63
Wijnands R., van der Klis M., 1999, ApJ, 514, 939
Zycki P. T., 2003, MNRAS, 340, 639